Alien Insect Species for Food and Feed

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While the use of alien insect species for food and feed can help to alleviate protein shortage and provide for a more sustainable feed production, their invasive potential should be considered.

Keywords: invasive alien species ; ecological impacts ; biological invasion

1. Introduction

The current prediction of human population increase (estimated in more than 9 billion by 2050) urges the need to provide sufficient nutritious food for all. That edible insects could help to ease future global food shortages and that WHO and FAO should support the use of insects as a food item was first suggested in 1975 by Meyer-Rochow in Australia [1]. However, the need to increase food production does not come cheap, as the availability of natural resources, arable land, and natural stocks are decreasing [2]. More recent estimates suggest that food production will have to increase by 60% to feed everyone [3].

Most of the arable land worldwide is used to grow grains, including soybean, rice, and wheat. These crops require large areas of arable land often in regions of ecological and economic global importance, contributing directly for the deforestation in several developing countries [4][5]. In addition, grain crops such as soybean have a high energy, water, chemicals, and soil footprint [6]. A huge proportion of these grains is produced for animal feed. Some animals (e.g., carnivorous fish) require a high protein diet for optimal growth [7]. Fish meal and soy meal both have high quality protein and are the most used protein sources for animal feeding [2].

Fishmeal and fish oil are obtained from natural stocks, representing an important percentage of the total world fisheries. The total world fish production has increased from 167 million tonnes in 2014 to 179 million tonnes in 2018, and the share of world fish production used for direct human consumption has increased from 146 in 2014 to more than 156 million tonnes in 2018. Almost all of the remaining 22 million tonnes (21 million in 2014) were destined to non-food products, of which 82 percent (18 million tonnes) (15.8 million in 2014) were processed to produce fishmeal and fish oil in 2018 [2][8].

Global feed production is the main cause of the environmental impacts of livestock production, representing up to 71% for eutrophication and 85% for climate change induced by pig production, 78.8% of environmental impact for poultry production, and up to 99% of marine eutrophication for farmed fish [9][10][11][12].

Therefore, due to a growing population and the environmental impacts currently caused by feed production and use, there is a clear need for alternative sources of protein for animal feeds and human food. However, these need to be obtained through sustainable methods. In this context, insects show great potential, as their production requires using warehouses rather than large field areas. They are good food converters, use much less water than livestock or agricultural crops, and have high protein values depending on species and life stage (larval, pupal, adult) [13].

When compared to other animal sources of protein, insects have higher edible portions, since they can be eaten whole (with only a few parts at times not being used) [13]. In addition, some insect species can be used for the conversion of organic wastes, which reduces the rearing costs [14][15].

Hence, insects are good alternatives for animal protein production and over the last years several companies have started to produce insects at a commercial scale for use as animal feed or even human consumption as snacks or cereal bars. In the EU, there are several features regarding the species of insects used for this end, namely not being pathogenic or not having adverse effects on plant, animal, or human health (e.g., diseases vectors). Additionally, these insects should not be listed either as protected or invasive alien species. These features were introduced in the EU by the commission, through the Regulation No 2001/999 (Annex IV), amended by the Regulation 2017/893 (Annex X), which authorizes the use of insect protein as an ingredient for aquaculture feed. The insect species currently reared in the EU are considered to fulfil all safety conditions legally determined for insect production for feed. To date insect species whose production has been authorized in the EU for this purpose are: Black Soldier Fly (*Hermetia illucens* Linnaeus, 1758) (Diptera: Stratiomyidae), Common Housefly (*Musca domestica* Linnaeus, 1758) (Diptera: Muscidae), Yellow Mealworm (*Tenebrio molitor* (Linnaeus, 1758)) (Coleoptera: Tenebrionidae), Lesser Mealworm (*Alphitobius diaperinus* (Panzer, 1797)) (Coleoptera: Tenebrionidae), House cricket (*Acheta domesticus* Linnaeus, 1758) (Orthoptera: Gryllidae), Banded cricket (*Gryllodes sigillatus* (Walker, 1869)) (Orthoptera: Gryllidae) and Field Cricket (*Gryllus assimilis* (Fabricius, 1775)) (Orthoptera: Gryllidae) [16].

In November 2021, another insect species was added to the list of currently authorized insect species for production of animal protein for feed-use in the EU, which was considered to have the safety requirements for feeding non-ruminants farmed animals, the domestic silkworm (*Bombyx mori* Linnaeus, 1758) (Lepidoptera: Bombycidae), a species already farmed for the silk market, and implement through the Regulation (EU) 2021/1925.

Moreover, also in 2021 with the Regulation (EU) 2021/1372 of 17 August 2021, the EU Commission Regulation lifted the “feed ban” rules for non-ruminants farmed animals, which now has authorized the production and use of insect proteins as an ingredient in formulated feeds for poultry, swine, pets (e.g., dogs, cats, birds or reptiles), and fur animals (e.g., Mink (*Mustela lutreola* (Linnaeus, 1761)) (Carnivora: Mustelidae)).

Some of these EU authorized species are exotic in the European territory (e.g., *A. diaperinus*, *G. sigillatus*, *G. assimilis*, and *B. mori*), and it is not clear how risk assessments related to insects being used as animal feed conducted in northern European countries, such as Belgium, the Netherlands, or France, can be representative of all EU bioregions, namely those in southern countries. Moreover, most insect species that are considered invasive in Europe were introduced unintentionally (e.g., Asian tiger mosquito *Aedes albopictus* (Skuse, 1894) (Diptera, Culicidae), Asian long-horned beetle *Anoplophora chinensis* (Forster, 1771) (Coleoptera, Cerambycidae)), by means of transportation of agriculture products, ornamental plants, or shipment transport, with just a small portion being deliberately introduced for biological control (e.g., the multi-coloured ladybeetle, *Harmonia axyridis* (Pallas, 1773) (Coleoptera, Coccinellidae), the whitefly parasitoid *Encarsia formosa* Gahan 1924 (Hymenoptera, Aphelinidae), and the ailanthus silkmoth *Samia cynthia* (Drury, 1773) (Lepidoptera, Saturniidae)) [17][18].

Exotic species can become stablished in new environments through a diverse evolutionary adaptability [19], and those with a favourable genetic variability if introduced in habitats with particular conditions and biotic pressures may often experience rapid evolutionary adjustments [20]. Moreover, species currently considered to have low potential as invasive species might increase this potential, as climate change pushes mean global temperature up, which may prompt the spread of insect species to higher latitude and altitudes (increasing the threat of pests in crops and forests) [21][22].

Increasing temperatures have enabled the spread of insect species to more northern parts of Europe with the additional aid of accidental transport by humans, or indirectly benefited by human infrastructure [23]. This northward movement of insect species is expected to cause more impacts to the environment, where insect pests may present both increase in population growth and metabolic rate in temperate regions [24]. Additionally, with a 2 °C higher mean global temperature, the crop losses for insect pests are estimated to escalate by 46, 19 and 31% for wheat, rice, and maize, respectively [24]. Furthermore, there is no likely saturation for the current invasion of species in a global scale with new pathways for introduction appearing constantly [25].

2. The Potential of Native Species

Despite the fact that current production of insect meals and products for human and animal feed mostly use Asian and neotropical species, it is already acknowledged that native species display good nutritional-values and conditions for mass production. The requirements for its mass production include a short life cycle, a high fecundity, and the ability to breed continuously in an artificial environment [26].

Recent studies showed that some Diptera, Coleoptera, and Orthoptera species present a high protein-value, comparable to soymeal, but lower than fishmeal. Nonetheless, the potential of order Diptera is still high as an alternative to fish meal by displaying a similar amino acid profile [27].

In fact, several insect species belonging to the orders Coleoptera and Diptera, which are part of the natural diets of Atlantic salmon (*Salmo salar* Linnaeus, 1758 (Salmoniformes, Salmonidae)), show adequate composition in polyunsaturated fatty acids (PUFA), nutrients necessary for fish growth. Therefore, they present significant potential to be used as a supplementation of the diets commonly employed to farm this fish [28].

Additionally, *Apis mellifera ligustica* Spinola, 1806 (Hymenoptera, Apidae), a subspecies of the European honeybee, showed great potential to be used as animal feed, due to its high protein content in the adult stage (51%). This species is also promising as a larva, presenting 30% of fat composition, which decreases over larval development, as well as it carbohydrates content [29].

Several blowflies show potential to be used as feed ingredients [30]. For instance, the blowfly (*Chrysomya megacephala* (Fabricius, 1794) (Diptera, Calliphoridae)) was evaluated as substitute of fishmeal in red Tilapia (*Oreochromis* sp.) production, with an average crude protein level of 54.4%. They contain all necessary amino acids to promote a suitable growth for this fish species. Feeds with 100% replacement of fish meal by maggot meals were successfully validated with no significant differences being recorded from a control commercial diet [31].

The Egyptian locust, *Anacridium aegyptium* (Linnaeus, 1764) (Orthoptera, Acrididae), occurring throughout most European territory, presents favourable PUFA percentages, although they have a low oil content, which can be used as co-product derived from the insect processing industry [32]. *Pseudochorthippus parallelus* (Zetterstedt, 1821) (Orthoptera, Acrididae) is another Orthopteran native to Europe with a suitable nutritional profile to be used as exotic pet food or livestock feed [33].

The common green bottle fly, *Lucilia sericata* (Meigen, 1826) (Diptera, Calliphoridae), is a blowfly found in most regions of the world [34]. Although they are known for causing myasis, with economic impacts for sheep producers [35], they present a high content in monounsaturated fatty acids and may be viable ingredient for animal feed [30].

In India, two preferred edible insect species have great potential to be used as animal feed: the ant *Oecophylla smaragdina* (Fabricius, 1775) (Hymenoptera, Formicidae) and the termite *Odontotermes* sp. Their protein content is 55.28% and 33.67%, their fat content is 14.99% and 50.93%, and their fibre is 19.84% and 6.30%, respectively. Their PUFA content is also important, with 8.19% for the first species and 2.59% for the second one [36].

The Owl butterfly, *Caligo memnon* Felder, 1866 (Lepidoptera, Nymphalidae) , native to South America also has a good potential to be used as animal feed, since it has a concentration of 62.5 mole % of α-linolenic acid (ALA) in total Fatty Acids, which is an essential omega-3 PUFA [37].

The dung beetle, *Acrossus rufipes* (Linnaeus, 1758) (Coleoptera, Scarabaeidae), is found in most of Europe and East Coast of the United States [38]. This species has great potential as animal feed, especially for fish, when considering their amino acid content. They exhibit essential amino acids, namely histidine and threonine, in higher concentrations than some cultivated fish species, such as catfish (*Clarias gariepinus* (Burchell, 1822) (Siluriformes, Clariidae)) or crayfish (*Procambarus clarkii* (Girard, 1852) (Decapoda, Cambaridae)) [39].

The stick insect *Cladomorphus phyllinum* Gray, 1835 (Phasmida, Phasmatidae), native to the Brazilian forests [40], showed potential as an alternative insect-based protein source. The dried samples showed a protein content of 64.6%, with the presence of essential amino acids, and a lipid content containing 57.03% of oleic acid, 15.94% of palmitic acid, 13.76% of linoleic acid and 10.76% of stearic acid [41].

The Chinese grasshopper *Acrida cinerea* (Thunberg, 1815) (Orthoptera, Acrididae), native to East Asia [42], was successfully used to replace the protein content of broilers feed, an addition of up to 150 g Kg^{-1}, and also showed potential to be mass reared [43].

The Mormon cricket, *Anabrus simplex*, Haldeman, 1852 (Orthoptera, Tettigoniidae), is native to North America, recorded for the USA and Canada [44]. This species has the potential to be used as broiler feed. No significant difference has been found between chicks fed with corn-soybean meal diet and the ones fed with corn-ground cricket when comparing weight gain and feed/grain ratio. Additionally, there was no adverse effect on the taste of the meat from the specimens fed the corn-cricket diet, as determined by a taste panel [45].

The field cricket native to China, *Teleogryllus (Macroteleogryllus) mitratus* (Burmeister, 1838) (Orthoptera, Gryllidae), synonym of *Gryllus testaceus* [44], has a crude protein of 58.3%, crude fat of 10.3%, chitin 8.7% and ash 2.96% (on dry matter basis), respectively. When fed as a replacement of 15% of soybean meal, it showed no significant differences with the control group (poultry feedstuff) in weight gain, feed intake, or gain/feed ratio [46].

The variegated grasshopper, *Zonocerus variegatus* (Linnaeus, 1758) (Orthoptera, Acrididae), is a common pest in Africa, and was recently reported in the United Kingdom [47]. However, its insect meal showed potential to be used as a fishmeal replacement for the African catfish, *Clarias gariepinus*, in which a replacement of 25% had no adverse effects on both the growth rate and nutrient utilization when compared to the control group [48].

The Chilean moth, *Chilecomadia moorei* Silva Figuero, 1915 (Lepidoptera, Cosiidae), whose larvae are known as butterworm, is native to Chile. They are used to feed insectivore exotic pets such as geckos. They are considered to be a good source of fat, due to its high fat content [49]. This species is popular among reptile owners since they have a distinct scent which attracts the lizards [50][51]. They are exported out from Chile to many countries and are not able to reproduce elsewhere, since they are dependent of the host tree *Retanilla trinervia* (Gillies and Hook.) Hook. and Arn. (Rosales, Rhamnaceae), endemic to Chile, and are considered a pest to this tree species [52][53].

Recently, the long-legged fly *Machaerium maritimae* Haliday, 1832 (Diptera, Dolichopodidae), a fly species native to western Europe, adapted to thrive in brackish waters, was reported as a potential feed ingredient for aquaculture due to its content in important omega 3 PUFA, including eicosapentaenoic acid (EPA), an essential nutrient for the healthy growth of marine organisms [54].

3. Native vs. Non-Native Species

Most of the insect species produced for both livestock feed and exotic pets' food are known to be exotic in regions such as Europe. They have some advantages when compared to native insect species, such as well-established rearing protocols for mass production and extensive studies to improve their productivity and potential to replace mainstream ingredients in formulated animal feeds (e.g., fish meal in aquafeeds). Nonetheless, native insect species are still interesting alternatives that are worth exploring, considering both the possible impacts caused by the escapes of exotic insects from pet shops and rearing facilities and the levels of some key nutrients on their biochemical profiles (e.g., PUFA). Both strengths and weaknesses, as well as opportunities and threats of using exotic or native species of insects as livestock feed are discussed below using a SWOT analysis (**Figure 1**).

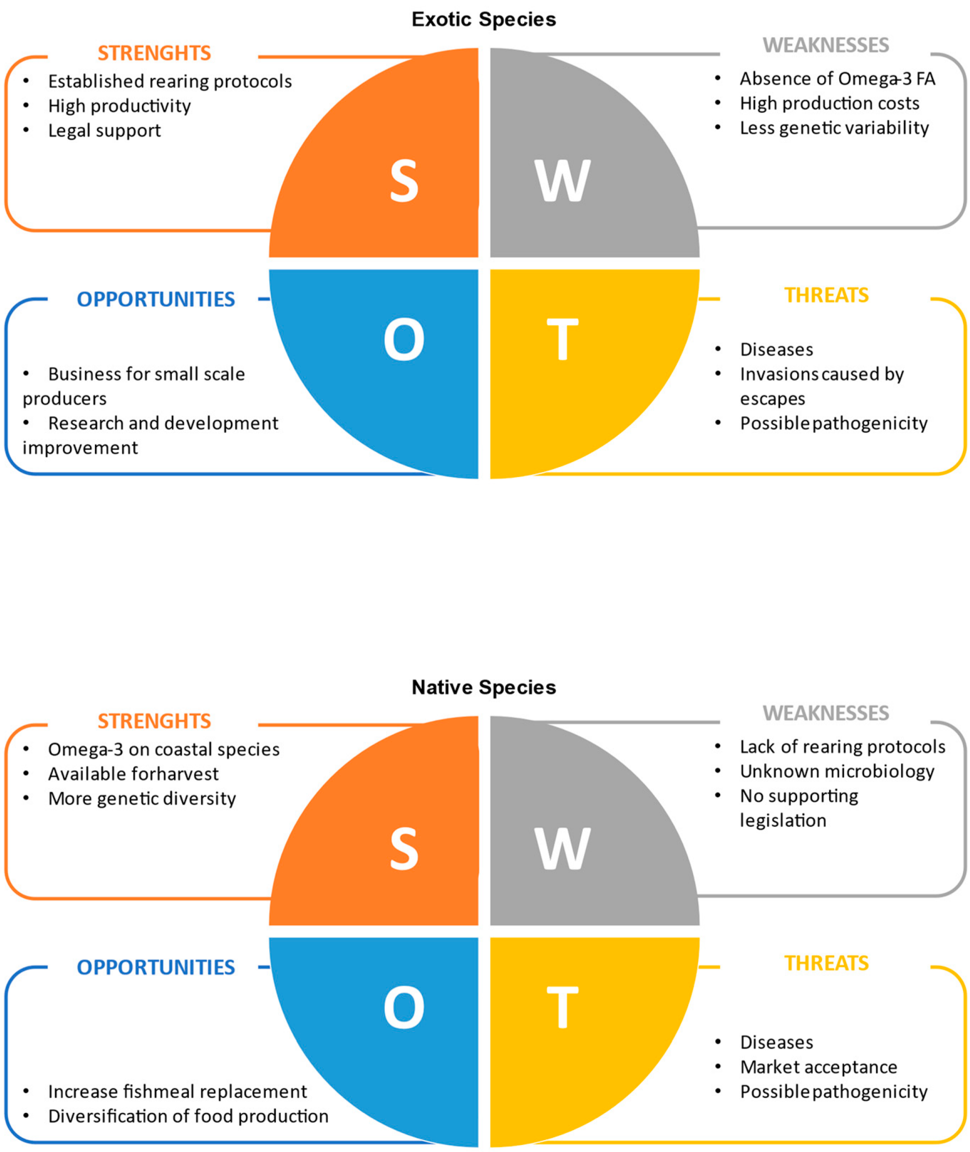

Figure 1. SWOT analysis (strengths, weaknesses, opportunities, and threats) associated with the use of exotic and native insect species for livestock feed and exotic pets' food.

Exotic species demand a higher energy supply for climatic control due to their need for higher temperature, namely when species originate from tropical regions (e.g., BSF). The use of native species can help to overcome challenges that the industry of formulated feeds currently faces associated with the diversification of omega-3 sources to manufacture aquafeeds for marine organisms.

The production of native species still lacks several studies, for instance regarding their microbiological content (particularly on *Salmonella* sp. or *Escherichia coli*, as their presence would make these species unsuitable for use as livestock feed ingredients). However, it is important to highlight that bacterial hazard for humans and animals related to insects originate from its rearing conditions, substrate, feed, handling, and processing, which needs to be carefully monitored to reduce the potential of these insects' species to act as vehicles of known zoonotic pathogens. Despite this, the presence of bacterial pathogens for animals found in substrates do not seem to replicate actively in insects, emphasizing the importance of substrate selection [55].

In Europe, one of the conditions to produce an insect meal for animal feed is that the target species cannot be listed as invasive according to the Regulation (EU) No 1143/2014 of the European Parliament and of the Council of 22 October 2014. This constraint is also an advantage to those advocating the use of native insect fauna to produce insect meals. However, the establishment of rearing protocols can be time consuming and financiallydemanding, considering that it can take hundreds or even thousands of generations to attain a desirable lineage, optimal for mass production, with individuals resistant to high density production and disease [26]. These features are already displayed by the insect species currently approved by the EU, due to decades of rearing, namely BSF which has been used for long in forensic entomology. Some of the species that hold potential to be used as feed already have well-established protocols for laboratory-scale culture that can be upgraded for industrial uses.

Regarding the legal framework in the EU on the production of insects for livestock feed, is currently limited to eight species (*H. illucens*, *M. domestica*, *T. molitor*, *A. diaperinus*, *A. domesticus*, *G. sigillatus*, *G. assimilis*, *B. mori*) considering that the origin of the substrate used for feeding the insects is not agricultural waste, or insects from the same species. The permission to use these insects as ingredients for formulated feeds employed in poultry and swine production was recently approved by the Commission Regulation (EU) 2021/1372, following the authorization of insects in aquaculture animals (EU reg.2017.893) and pet which was already permitted. Other countries outside the EU (e.g., the USA and Brazil), current regulatory guidelines for the production of insects for livestock feed do not have a specific legislation. These fall under the novel foods category, meaning that rules that apply are those for any other food operator, considering that its production, packaging, transportation, and storage fall under the good hygiene conditions and that products are properly labelled [56].

The production of native insect species can increase the biodiversity of food production, which today is considerably low, if one considers that only a dozen of species of animals provide up to 90% of all of the animal protein consumed globally and just four crop species provide half of all plant based calories for human diets [57]. Moreover, the production of native insect species can help to overcome the challenges of inbreeding, which reduces the intraspecific genetic variability, possibly making farmed populations more susceptible to disease that can cause significant economic losses [58].

Moreover, the insect production for livestock feed and pet's food, faces the challenge of the possible allergenicity carried by the presence of IgE Immunoglobulin or tropomyosin, which is known for causing allergic reactions for human consumers, but also for pets such as dogs [59][60]. In addition, insects can accumulate heavy metals in their tissues if these are present in their feeding substrates (e.g., cadmium from wheat, rice, mussels and corns), as well as pathogens from the rearing environment, which must be carefully considered when rearing insects for feed [61].

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